Highlights

- We assess crop-livestock integration beyond the farm scale based on farm surveys and assessment
- Cooperating farms gain access to normally underutilised local resources
- Resources accessed via cooperation are mostly used to increase farm production intensity
- Recoupling crops and livestock via cooperation between farms generates few environmental benefits
- Cooperating farms are better equipped to grow in period after milk quota abolition

Does the recoupling of dairy and crop production via cooperation between farms generate environmental benefits? A case-study approach in Europe.

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Abstract

The intensification of agriculture in Europe has contributed significantly to the decline of mixed crop-livestock farms in favour of specialised farms. Specialisation, when accompanied by intensive farming practices, leaves farms poorly equipped to sustainably manage by-products of production, capture beneficial ecological interactions, and adapt in a volatile economic climate. An often proposed solution to overcome these environmental and economic constraints is to recouple crop and livestock production via cooperation between specialised farms. If well-managed, synergies between crop and livestock production beyond farm level have the potential to improve feed and fertiliser autonomy, and pest regulation. However, strategies currently used by farmers to recouple dairy livestock and crop production are poorly documented; there is a need to better assess these strategies using empirical farm data. In this paper, we employed farm surveys to describe, analyse and assess the following strategies: (1) Local exchange of materials among dairy and arable farms; (2) Land renting between dairy and arable farms; (3) Animal exchanges between lowland and mountainous areas; and (4) Industrially mediated transfers of dehydrated fodder. For each strategy, cooperating farm groups were compared to non-cooperating farm groups using indicators of metabolic performance (input autonomy, nutrient cycling and use efficiency), and ecosystem services provision. The results indicate that recoupling of crop and dairy production through farm cooperation gives farmers access to otherwise inaccessible or underutilised local resources such as land, labour, livestock feed or organic nutrients. This in turn leads to additional outlets for by-products (e.g. animal manure). Farmers' decisions about how to allocate the additional resources accessed via cooperation essentially determine if the farm diversifies, intensifies or expands operations. The key finding is that in three of the four crop-livestock integration strategies assessed, these newly accessed resources facilitated more intensive farming practices (e.g. higher stocking rate or number of milking cows per hectare) on cooperating dairy farms relative to non-cooperating, specialised dairy farms. As a consequence, cooperation was accompanied by limited environmental benefits but helped to improve resource use efficiency per unit of agricultural product produced. This article provides a critical step toward understanding real-world results of crop-livestock cooperation beyond the farm level relative to within-farm crop-livestock integration. As such, it brings practical knowledge of vital importance for policy making to promote sustainable farming.

Keywords: crop-livestock integration, farm specialisation, ecosystem services, resource use efficiency, nutrient cycling, dairy production

1. Introduction

Contemporary agriculture through its direct impacts on land use and ecosystems, and on regional and global cycles of carbon, nutrients and water is one of the main drivers of environmental change (Foley et al., 2011). Many negative agricultural impacts are related to intensification and specialisation of farming systems in industrialised countries (Maréchal et al., 2008; O'Sullivan et al., 2015). In Europe, mixed crop-livestock farms have been declining since 1970 (Ryschawy et al., 2013) and by 2010 only 14 % of farm holdings were mixed with both crops and livestock, while 52 % were specialised in cropping, and 34 % were specialised in livestock keeping (Eurostat, 2013). These specialised farms are often dissociated from land and its natural cycles (Naylor et al., 2005; Peyraud et al., 2014), and as a result generally exhibit low diversity, high-input use, and low resilience in the face of sudden economic or environmental shocks (Oomen et al., 1998).

Given that farmers now have to operate in a context characterised by unprecedented change and high uncertainty, such as ever-more limited and costly production resources, stricter environmental regulations, volatility in agricultural product prices and increasing frequency of extreme climatic events (Lebacq et al., 2015), continuing along a trajectory of specialisation in dairy and arable farming potentially threatens the long-term sustainability of these food production systems. Specialised farms are more vulnerable to increases in the cost of inputs to production than are mixed farms that can source inputs to production from exchanges between the crop and livestock enterprises on the farm (i.e. manure for animal feed). Similarly, a decrease in price received for crop or livestock products is more threatening to a specialised farm producing only one output than it is to a mixed farm with a diversity of outputs (Lebacq et al., 2015). Furthermore, the lower crop diversity and system flexibility generally observed on specialised farms relative to mixed farms leaves the former less well-equipped to adapt their systems in the face of climate shocks. Diversified systems, such as crop-livestock systems (where local integration of crops and livestock systems occurs), therefore appear to be an interesting alternative and path forward for agricultural development (Lemaire et al., 2014). Recoupling crop and livestock production is often advocated as an approach to improve properties of agricultural systems such as productivity (Herrero et al., 2010; Peyraud et al., 2014; Soussana and Lemaire, 2014), resource use efficiency (de Moraes et al., 2014; Schiere et al., 2002; Sulc and Tracy, 2007; Veysset et al., 2014; Villano et al., 2010), autonomy (Ryschawy et al., 2013) and resilience (Havet et al., 2014; Peyraud et al., 2014; Salton et al., 2014) and to provide ecosystem services, such as improved soil fertility, pest regulation and carbon sequestration (Bonaudo et al., 2014; Lemaire et al., 2014; Peyraud et al., 2014; Sanderson et al., 2013; Soussana and Lemaire, 2014; Sulc and Franzluebbers, 2014).

Achieving this recoupling at farm-level on specialised dairy and arable farms will be challenging for farmers: resource and infrastructural constraints on individual specialised farms will make it difficult for farmers to evolve their production system to one where recoupling of crops and livestock can easily occur. As an alternative, several authors (Bell and Moore, 2012; Bell et al., 2014; Franzluebbers et al., 2014; Russelle et al., 2007) have proposed that recoupling can be achieved at larger scales than the farm through cooperation, partnerships and contracts between specialised crop and livestock farms. This is an attractive solution in the current high input cost and resource limited climate as it allows some of the synergies normally provided by within-farm integration to be obtained, but with much smaller increases in farm workload, complexity of rotations, skills and infrastructure on individual farms involved. Integrating crops and livestock via cooperation among specialised farms also has the advantage that a greater quantity and diversity of production resources are accessible compared to those available when integration takes place internally at the farm scale.

Yet, research in this domain remains, except for a few exceptions, largely at a theoretical and conceptual level (Ryschawy et al., 2014; Veysset et al., 2014; Villano et al., 2010), and therefore practical messages for policy makers and farmers are lacking (Moraine et al., 2014; Peyraud et al., 2014; Russelle et al., 2007; Sulc and Franzluebbers, 2014). For example, little is known about the appropriate scale at which to promote integration between crops and livestock or about the difficulties that farmers encounter when cooperating with another farmer to integrate their productions. As a consequence, there are insufficient empirical research studies to assess the performance of integrated crop-livestock systems at scales beyond the farm (Bonaudo et al., 2014; Tanaka et al., 2008). In particular, questions remain as to whether collaboration among specialist farms might achieve the same range of metabolic (improved input autonomy, nutrient use efficiency) and ecological (improved pest biocontrol, higher soil carbon sequestration) synergies as within-farm integration (Peyraud et al., 2014; Russelle et al., 2007).

The objective of this study was to assess the benefits and drawbacks of integrating crops and livestock via cooperation between farms compared to integrating them at the farm scale or keeping them separated on individual specialised crop and livestock farms. Four crop-dairy livestock integration strategies were assessed using empirical farm data from case studies in different biogeographical regions of Europe. The strategies assessed were: (1) Local exchange of straw for manure among dairy and arable farms; (2) Temporary land renting between dairy and arable farms; (3) Animal exchanges between lowland and mountainous areas; and (4) Industrially mediated transfers of dehydrated fodder. By comparing non-cooperating baseline farms (specialised and mixed) with cooperating, specialised farms in each case study area, it was possible to identify the benefits and drawbacks, at both farm and beyond farm levels, of the different integration strategies, in particular relating to system metabolism (nutrient use efficiency and autonomy) and ecosystem services provision (such as soil fertility, pest regulation and carbon sequestration). It was hypothesised that cooperation between specialised arable and livestock farms will improve farm level environmental performances due to better management of natural resources and enhanced provision of ecosystem services. More precisely, we first hypothesised that cooperation between farms specialised in crop or dairy livestock production can help close nutrient cycles and mitigate external inputs of fertiliser and feed beyond the farm level. Second, we hypothesised that the production of ecosystem services will be greater on cooperating farms relative to non-cooperating, specialised farms since it is expected that recoupling crop and livestock production will capture positive ecological interactions such as manure recycling on arable soils and legume fodder insertion in arable crop rotations.

One may want to distinguish between cooperation and integration among specialised farms. In the former, flows of products are generally organised through a marketplace in a pure economic logic where transport of products depends only on costs, with little consideration for the benefits linked to integration, whereas in the latter, there is a collective organisation of the landscape structure such that crop and livestock activities in a collection of farms are considered simultaneously to optimally manage resources and promote ecosystem services (Moraine et al., 2014). However, the difference between these terms can at times be disputed. For example, all the case-studies considered in this paper involved some market mediated cooperation among specialised farms but such cooperation generally took place through two way material exchanges and was designed to improve environmental benefits (such as increased nitrogen fixation by legumes, increased carbon sequestration by incorporating manure in soils, natural pest regulation, preservation of biodiversity, etc.). Therefore, in the following sections we use cooperation as a general term that encompasses a wide range of interactions among specialised farms.

2. Materials and Methods

2.1 Case studies

Case studies were chosen to ensure a diversity of forms of cooperation from different biogeographical regions (Atlantic, Alpine and Mediterranean), and were located in different European countries. The four case studies assessed were located in: Ebro River Basin, Aragon, Spain; Winterswijk, The Netherlands; Thurgau and Grisons, Switzerland; and Brittany, France. The strategies to recouple crop and livestock production are illustrated in supplementary Figure S 1.

2.1.1 Ebro Basin, Aragon, Spain

The Ebro River Basin of the Aragon region is situated in the northeast of Spain. The climate in the region is mainly Mediterranean semiarid, with precipitation ranging from around 290 to 400 mm/yr (Table 1). Due to a severe hydric deficit in the area, dairy farming systems are linked to the irrigated valley bottoms of the Ebro River and some of its tributaries. The dairy farming system in the Ebro Basin involves permanent housing of cows and zero-grazing with cut irrigated forages fed indoors

(Barrantes et al., 2009). Land use involves irrigated lands, sown mainly with maize for silage, Italian ryegrass and alfalfa. The most common land use is double cropping (two crops grown successively during one year) of Italian ryegrass in winter and silage maize in spring-summer. High levels of concentrate feeds are used which consist mainly of locally produced corn and barley and imported (from United States, Brazil and Argentina) soybean meal. As dairy farms in the area don't generally grow cereals, the straw they require for animal bedding and for feeding to heifers as low quality forage is often obtained through exchange for dairy manure with neighbouring arable farms. On arable farms that cooperate with dairy farms, conventional tillage is predominant as manure has to be incorporated into the soil whereas non-cooperating arable farms practice mostly no-till or min-till and grow mainly cereals, such as barley and wheat. The form of cooperation taking place was the exchange of solid manure produced on dairy farms for barley straw produced on neighbouring arable farms, allowing dairy manure to be spread on crop land (improving soil fertility on arable farms) and providing straw for use as bedding material on dairy farms. Cooperation is not governed by a contractual agreement and so the risk to farmers is not covered from year to year.

2.1.2 Winterswijk, The Netherlands

Winterswijk is located in the Eastern part of the Netherlands in the province of Gelderland. The soil type together with good rainfall makes the municipality highly suitable for grass production. Agriculture accounts for 61% of the land use in Winterswijk, with specialised dairy farming the most important agricultural sector in the region (150 farms). Land use in the municipality is dominated by grass and maize for silage (Korevaar and Geerts, 2012) while other crops are cereals and potatoes with about 10 – 15 arable farms specialised in potato production (Table 1). The form of cooperation taking place is the short-term renting of land between dairy farms and neighbouring arable farms specialised in potato production. This form of cooperation allows the introduction of temporary grassland in potato crop rotations and the spreading of dairy slurry on potato crop fields. The renting of fields generally takes place when dairy farmers renew their grassland (on average every 5 years). This allows arable famers to extend their acreage by planting a potato crop on the dairy farmer's field in spring.

The relative small size of these arable farms means that the growing of potatoes on the rented fields of dairy farms is very important to the arable farmer as it allows him to have long potato-based crop rotations to better control soil-borne diseases.

2.1.3 Cantons of Thurgau and Grisons, Switzerland

The cantons of Thurgau and Grisons are situated in the northeast and east of Switzerland, respectively. They are representatives of lowland and mountainous areas. Pronounced differences in altitude and climate between the two cantons is the main reason for the vast difference in the productivity of their soils, with those of the lowland Thurgau canton being more productive and therefore more suitable for intensive agriculture than the soils of the mountainous Grisons canton, which are more suitable for extensive agriculture (Table 1). Grassland farming is dominant in both cantons, with dairy cattle being the dominant grazing livestock. Cereal and root crop production (primarily sugar beet and potato) takes place on about one quarter of the utilised agricultural area (UAA) in Thurgau compared to only about 2% of UAA in Grisons (Swiss Federal Statistical Office, 2013).

Concentrate feed autonomy (currently around 50% in Switzerland) could be improved through collaboration between the cantons of Thurgau and Grisons, whereby, more cattle with lower feed requirements such as lowland heifers are fed on mountain grassland, and cattle with higher feed requirements such as dairy cows are fed on lowland grass. The form of cooperation taking place is the sale, by lowland farmers, of weaned female dairy calves to mountain farmers. The mountain farmers raise the heifers and then sell them back to the same lowland farmer when they are pregnant and close to calving. Cooperation takes place via a standardised contract with the price being determined by age at first calving.

This form of cooperation allows cooperating lowland and mountain farmers to better exploit available resources. The lowland dairy farmer may use the land (and time) previously used for the raising of young stock, to either grow crops or to increase cattle numbers and produce more milk using highly productive lowland grass. This grassland resource can be grazed to its full potential when stocked with dairy cattle whereas it remained under grazed when stocked with young animals.

2.1.4 The Coopédom cooperative (Domagné, Brittany, France)

The climate (temperate oceanic) and soil context in the Brittany region has favoured the development of animal production such that it is France's leading region for animal production (Table 1). Even though 94% of the regions UAA is allocated to animal production (grazing, and feed and forage crops), the region is highly dependent on protein crop imports (particularly soybean meal). The Coopédom agricultural cooperative, realising the needs of its 700 members (mostly dairy farmers) for high quality forages, adopted the industrial process of dehydrating forages (mainly grass, alfalfa and silage maize) to preserve their quality. The cooperative also harvests and transports forages for its members. The facility to dehydrate alfalfa makes it a viable home-grown protein crop with potential to reduce dairy farmer's dependency on imported soybean meal. The dehydration process uses a biomass (40% miscanthus (Miscanthus x giganteus) and 60% wood from forest or sawmills) furnace and a coal furnace. Coopédom currently harvests approximately 400 ha of miscanthus per annum for fuelling its biomass furnace, which provides 30% of the energy needs of the cooperative. Some of this miscanthus is produced on dairy farms where it is sown on land normally reserved for annual crops. The form of cooperation taking place was the dehydration and supply of forage crops (primarily alfalfa) through an agricultural cooperative fuelled by miscanthus grown by the cooperative's members.

Table 1. Key characteristics of the selected study areas.

	Ebro Basin, Spain	Winterswijk, The Netherlands	Switzerland		Brittany, France
Biogeographic region	Mediterranean	Atlantic	Alpine		Atlantic
Study area (km²)	2607	139	991 (Thurgau)	7105 (Grisons)	706
Administrative unit	Catchment	Municipality	Canton	Canton	Region
Maximum distance between sampled farms (km)	100	18	36	73	40
Dominant soil type	loam to silty loam	sand	loam	loam to sandy loam	Loam to clay
Climate (average annual temp and average annual rainfall)	14.2°C; 360 mm	10.3°C; 848 mm	8.7°C; 1075 mm	8°C; 1150 mm	11.5°C; 1210 mm
Land use in % of total agricultural area	Cereals = 55; Maize = 12; Alfalfa = 15; Ryegrass = 2; Other crops = 5	Cereals = 4; Grassland = 65; Silage maize = 22; Potato = 6; Other crops = 3	Cereals = 17; Oilseed = 2.5; Grassland = 60; Perennial crops = 5; Others = 15	Cereals = 1.5; Grassland = 94; Perennial crops = 1; Others = 3	Cereals = 34; Oilseed = 3; Grassland = 63
Number of farms in study area	719	331	2832	2538	1445
Farm type by % of total farms	Dairy = 1; Pig and poultry = 8; Beef = 4; Sheep = 5; Arable = 80 Mixed = 2	Dairy = 60; Pig and poultry = 12; Beef = 13; Arable = 4; Mixed = 11	Dairy = 24; Pig and poultry= 9; Beef = 5; sheep/goat = 8; Arable = 22; Mixed = 33	Dairy = 22; Beef = 39; sheep/goat = 21; Arable = 6; Mixed = 11	Dairy = 33; Beef = 10; Pig and poultry = 13; Sheep/goat = 11; Arable = 16; Mixed = 11; Other = 5
Average farm size in ha (for dairy, arable and mixed farms in the study area)	NA	24 (average for dairy, mixed and arable farms)	Dairy = 21; Arable = 19; Mixed = 28	Dairy = 29; Arable = 26; Mixed = 31	Dairy: 59; Arable: 18; Mixed: 56
Average stocking rate on dairy and mixed farms (LU ha^{-1})	6.5 (dairy farms of Aragon)	1.64 (on dairy and mixed dairy combined)	Dairy = 1.69; Mixed = 1.21	Dairy = 0.96; Mixed = 1.43	1.4 (on dairy and mixed combined)
Average stocking rate on beef, pig and poultry farms (LU ha^{-1})	Beef = 0.45; Sheep = 0.22; Pig = 0.18	NA (most pig and poultry farms have hardly any land)	Beef = 1.3; Pig = 48; Poultry = 5	Beef = 0.9; Pig = 4.1; Poultry = 2.9	Beef = 0.9 Pig and poultry = NA (but most farms have hardly any land)
Average milk yield of dairy and mixed farms (kg milk/cow/year)	NA	8000	Lowland dairy = 6987; Lowland mixed = 7788 [a]	6164 [a]	7263
Dominant crop species and average yield (t DM/ha) for arable and mixed farms	Winter cereals (dryland) = 2.5; Grain maize = 12; Alfalfa = 15.5	Potato = 9.4; Silage maize = 14.4; Wheat = 5.5; Barley = 6.4; Sugar beet = 13.2	Wheat = 5.8	NA	Wheat: 7.6; Maize: 9.6

[a] These figures are not specific to Thurgau or Grisons, but to the lowland and mountainous areas they represent.

2.2 Research approach employed and data collection

In order to assess the potential for the different strategies to recouple crop and livestock production, a farm survey design was employed in each case study to compare two existing farm types: non-cooperating, specialised and/or mixed farms (i.e. the baseline farms) were compared to cooperating, specialised farms (i.e. farms cooperating at district level). Cooperating farms consisted of both dairy livestock and crop farms that employed one of the four crop-livestock integration strategies already introduced above (see supplementary Figure S 1).

For each case study and its associated crop-livestock integration strategy a number of baseline farms and cooperating farms were sampled. The baselines to be sampled for each case study were defined based on the type of farms cooperating together. In general, the first baseline consisted of non-cooperating, specialised farms and had a sampling density of 4-8 non-cooperating, specialised dairy farms and 5-15 non-cooperating, specialised arable farms located nearby. The second baseline group, which was only relevant or available for some of the case studies, consisted of non-cooperating, mixed farms (farms with interdependent livestock and arable enterprises) and had a sampling density of 3-4 mixed farms.. The purpose of this baseline was to allow comparison of the performance of mixing crops and livestock at the farm level (within-farm) versus beyond the farm level (among-farm). The two baseline groups were compared with 6-11 specialised farms that cooperate for mutual benefit. The number of baseline and cooperating farms sampled in each case study is outlined in Table 2. More details of the farm types sampled in each case study are provided in supplementary Tables S 1-4.

Table 2. Baseline and cooperating farms surveyed per case study.

Farm group	No. of farms sampled (n=84 in total)			
	Ebro Basin, Spain	Winterswijk, The Netherlands	Thurgau and Grisons, Switzerland	Brittany, France
Non-cooperating,	4	4	8 (4 , 4)[a]	7

specialised dairy				
Non-cooperating, specialised arable	5	15[b]	NR	NR
Mixed dairy	4	3	NR	NR
Cooperating, specialised dairy	5	3	8 (4, 4) [c]	11
Cooperating, specialised arable	4	3	NR	NR

[a] Four non-cooperating lowland dairy farms and four non-cooperating mountain dairy farms.

[b] Surveyed farms were located approximately 40km from the Winterswijk municipality in the provinces of Gelderland, Overijssel and Drenthe.

[c] Four lowland dairy farms (no heifers) and four mountain heifer rearing farms.

NR, not relevant

A number of baseline and cooperating farms were chosen from each study area based on their representativeness in terms of land use, farm size, stocking rate, milk yield per cow, and dry matter yield per dominant crop type (Table 1). Note that cooperating farms were not selected based on their exact representativeness of dairy and arable farms within the considered case studies but were selected in order to capture the dominant form of cooperation between farms. Farms were then surveyed to collect data on location (distance between farms), interaction with neighbouring farms (contract based or verbal, quantities exchanged, amount exchanged etc.), farm structure (land use, labour force, output, livestock etc.), farming practices (chemical input, irrigation, tillage etc.), and farm agronomic and economic performances (crop and animal productivity, farm income, etc.). The farms were then grouped according to type (non-cooperating dairy, mixed dairy, cooperating arable etc.) for analysis of each group followed by comparisons between certain groups. The empirical farm data used to calculate indicator values were collected by case study leaders for the year 2013 (in some cases supplemented with data from 2012). Interviews with farmers took place during the winter season 2014.

Appropriate indicators of metabolic performance and ecosystem services provision were used to conduct a multi-criteria assessment of each crop-livestock integration strategy. Some general indicators were calculated for all case studies, whereas others were specific to a case study, depending on the expected benefit of the cooperation. Indicators of metabolic performance included: farm-gate N surplus (after Nevens *et al* 2006); N use efficiency; district N autonomy; concentrate feed autonomy; forage autonomy; cropping intensity (FAO, 1997) and stocking rate. Indicators of ecosystem services provision included: crop yield; milk production; number of pesticide applications; % UAA under permanent grassland or legumes; crop rotation duration; and crop diversity as measured using the Shannon Diversity Index (after Benin *et al* 2004). A short list describing the non-self-explanatory indicators is provided in Table 3.

Table 3. Indicators of metabolic performance and ecosystem services provision and.

Indicator	Unit	Description
Stocking rate	LU ha^{-1}	Number of livestock units divided by the land area on the farm used to produce feed (forage + grain feed) for livestock
Farm-gate N surplus	kg ha^{-1} or kg kg^{-1}	Total N input - total N output. Expressed per hectare of UAA or per kg of N in sold agricultural products [a, b]
Nitrogen use efficiency	kg kg^{-1}	Total N in sold products divided by total N input [c]
District N autonomy	%	N input via material exchange of straw or manure, biological fixation and deposition divided by total N input to the farm
Concentrate feed autonomy	%	Home-grown cereal grain fed to livestock divided by total concentrates (protein and energy) fed to livestock
Forage autonomy	%	Home-grown forages (grazed and cut) fed to livestock divided by the total forages fed to livestock
Shannon diversity index		SDI = where α_ι = area share occupied by ι^{th} crop variety within the total planted area.
Cropping intensity		Ratio between irrigated crop area (where double cropping areas are counted twice respectively) and physical area equipped for

		irrigation (FAO, 1997)

[a]Stock changes (e.g., conserved forages, straw, etc.): a stock increase was considered as an output of N and a stock decrease was considered as an input of N to the farm.

[b]Farm-gate N surplus was calculated using the following N inputs: mineral N; N in plant products; N in concentrate feed; N in irrigation water; N fixation; N deposition. N outputs included: N in exported crops; N in milk sold; N in animals sold and N in manure exported off the farm.

[c]Nitrogen use efficiency was calculated using the following N inputs: mineral N; N in plant products; N in concentrate feed; N in irrigation water; N fixation; N deposition. N outputs included: N in exported crops; N in milk sold; and N in animals sold

Indicators were first calculated at the farm level and then averaged for each farm group. For each indicator and case-study, the comparison between baseline and cooperating groups were performed through simple Anova followed eventually by multiple comparison Tukey tests. All the statistical treatments were performed with R.

3. Results

3.1 Local exchange of materials among dairy and arable farms (Ebro Basin, Aragon, Spain)

Characteristics of the studied farm groups in the Ebro Basin are presented in Table 4. The cooperating, specialised dairy group had the highest mean milk production per hectare of feeding area producing over 45,000 litres. Milk yield per cow was approximately the same across the three dairy farm groups ranging from 10,405 to 10,510 litres. In terms of tillage system, the non-cooperating, specialised arable group is different from the other groups with only 6 % of its UAA under conventional tillage compared to between 70 and 97 % for the other groups.

Table 4. Characteristics of the Ebro Basin farm groups; mean values ± standard deviations

Farm characteristic	Non-	Non-	Mixed	Cooperating,	Cooperating,

	cooperating, specialised dairy	cooperating, specialised arable	dairy	specialised dairy	specialised arable
Utilised agricultural area (ha)	35 ± 7.2	195 ± 85	306 ± 223	29.6 ± 22.8	159 ± 171
Stocking rate (LU ha^{-1})	3.5 ± 0.6	-	2.7 ± 1.9	6.8 ± 4.9	-
Milk production (m^3 ha^{-1})	25.2 ± 4.3	-	17.7 ± 8.6	45.5 ± 31.3	-
Conventional tillage area (%)[a]	73 ± 31	6 ± 9	70 ± 22	90 ± 22	97 ± 7
Irrigated area (%)	100 ± 0	26 ± 37	97 ± 6	82 ± 25	85 ± 29
Forage area (%)	94 ± 7	9 ± 12	51 ± 14	75 ± 35	29 ± 12
Cereals and oilseeds area (%)	6 ± 7	75 ± 21	47 ± 11	22 ± 32	70 ± 11

[a] All tillage, irrigation and land use areas are expressed as a percentage of the total UAA of the farm

Potential benefits of material exchanges between specialised farms were assessed via hypothesis testing. We firstly hypothesised that cooperation would: 1) reduce mineral fertiliser use on cooperating, specialised arable farms relative to their non-cooperating counterparts; and 2) limit over application of manure on cooperating dairy farms thus preventing highly positive farm-gate nutrient budgets. However, the mineral N fertiliser input per hectare on cooperating arable farms was more than double that used on non-cooperating arable farms (Figure 1(b)). Such results were due to intensive arable cropping on cooperating arable farms as revealed by intensive soil tillage and irrigation (Table 4). Contrary to expectations, cooperation did not prevent highly positive farm-gate nutrient budgets: results showed that the N surplus per hectare was higher on cooperating dairy farms (496 kg N surplus/ha) than on their non-cooperating counterparts (344 kg N surplus/ha) (Figure 1(a)) although this result was not identified as being statistically significant. Expressing farm-gate N surpluses per unit of agricultural product showed non-cooperating (2.20 kg N surplus/kg N sold in products) and cooperating (2.15 kg N surplus/kg N sold in products) dairy farms to have similar N surpluses.

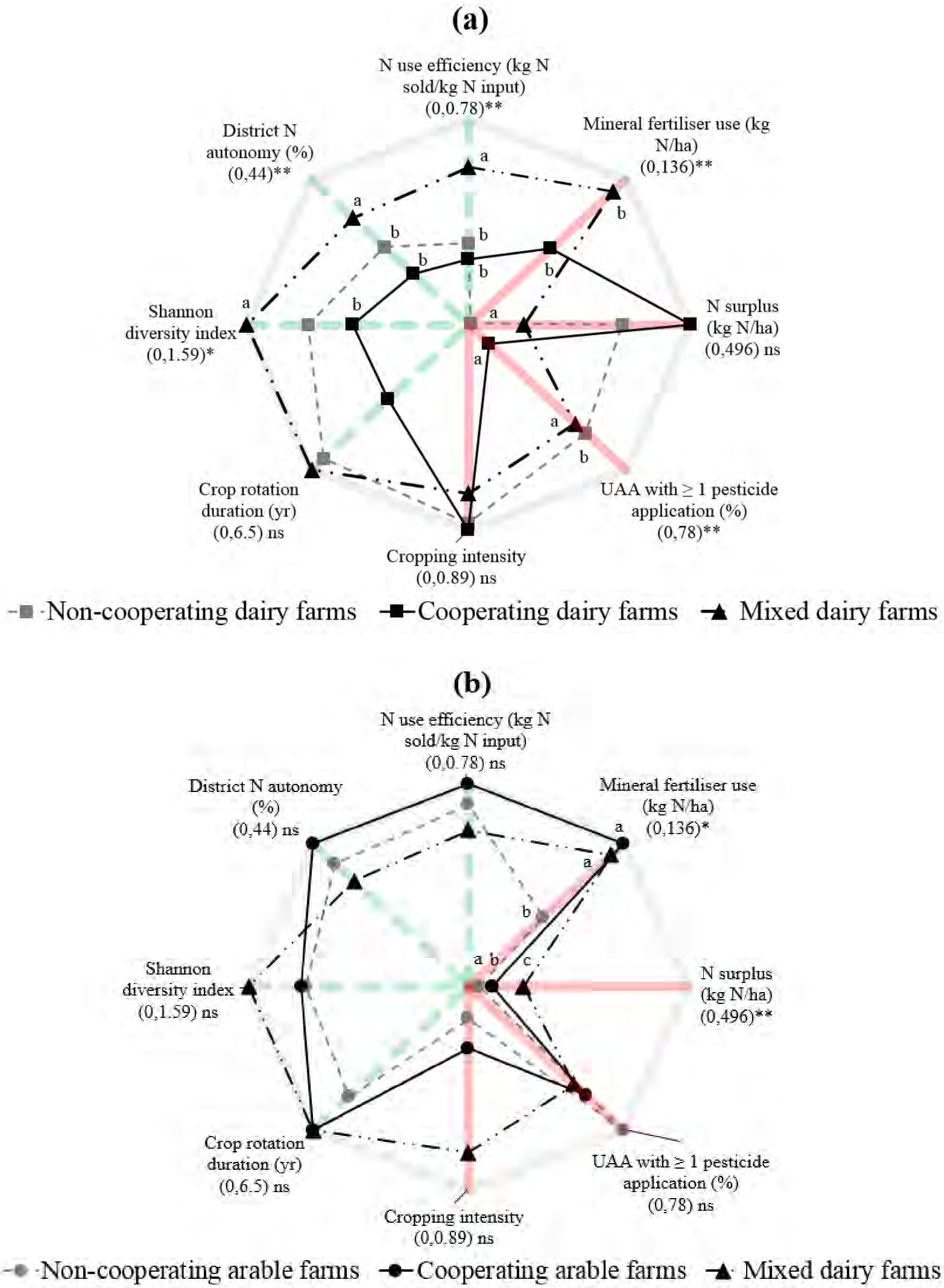

Figure 1 Comparison between Ebro Basin farm groups: radar chart (a) compares non-cooperating, cooperating and mixed dairy farms; and radar chart (b) compares non-cooperating and cooperating arable farms and mixed dairy farms. Higher indicator values on green axes are

indicative of better environmental performance (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of poorer environmental performance (i.e. less self-sufficient in inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1, ** for p<0.05, and ns for non-significant). The min and max value for each indicator's axis is provided in brackets after the indicator label.

It was secondly hypothesised that cooperation helps to increase the fraction of the nutrients entering farm gates that comes from within the cooperating group (for both arable and dairy farms), thus improving fertiliser autonomy of the cooperating farms. To test this hypothesis, the district N autonomy was calculated by dividing the sum of N input via material exchange of straw or manure, biological fixation and deposition by the total N input for each farm group. Contrary to expectations, results showed that cooperating dairy farms exhibited lower district N autonomy (16%) than non-cooperating dairy farms (24%) due primarily to a large amount of imported concentrate feed and forages (Figure 1(a)) coming from outside the cooperating farm group.

Lastly, aside from the expected benefits of this cooperation, a major drawback could be that cooperation between specialised arable and dairy livestock farms would limit the crop species diversification of arable farms compared to mixed farms and may thus result in short, simplified crop rotations. Results showed that cooperating arable farms, when compared to mixed farms, exhibited: 1) much lower land use diversity as measured by the Shannon Diversity Index (Figure 1(b)); 2) shorter crop rotations (Figure 1(b)) with lower species diversity (data not shown); 3) smaller % of UAA alternating spring and winter crops (25% compared to 53%); and 4) greater % of UAA with two or more subsequent cereals (70% compared to 47%). Similarly in Figure 1(a) it can be seen that cooperating specialised dairy farms, when compared to mixed farms, have lower land use diversity and shorter crop rotations. These results provide further evidence of the higher intensity of farming taking place on cooperating dairy farms relative to non-cooperating, specialised and mixed dairy farms. The percentage UAA with ≥ 1 pesticide application was the only indicator showing lower intensity of farming on cooperating farms relative to non-cooperating, specialised farms (Figure 1(a) and Figure 1(b)). Comparing mixed farms with cooperating dairy farms in Figure 1(a) shows that the former are more diverse, autonomous, and efficient, and pose a lower pollution risk per hectare of farmed area.

The increase in farming intensity on cooperating dairy farms as indicated by higher stocking rate, and on cooperating arable farms as indicated by the cropping intensity and input use has restricted the benefits that these farming systems would otherwise have realised as a result of cooperation, such as lower N surplus per hectare. As a result of cooperation, dairy farms have access to a greater land area on which to spread excess manure. The result is a doubling of the stocking rate on cooperating dairy farms relative to specialised dairy farms as they take advantage of new outlets for manure acquired through material exchange. As this increase in stocking rate is aligned only with the farming systems ability to manage manure and not with its ability to produce livestock feed, higher volumes of concentrate feed and forages must be imported onto the farm to sustain the system. Hypotheses pertaining to the expected benefits of material exchanges between farms were proved to be false. This would appear to be a result of the intensification observed on both cooperating dairy and cooperating arable farms.

3.2 Land renting between dairy and arable farms (Winterswijk, The Netherlands)

In Winterswijk, cooperation through land renting is generally not covered by a contractual agreement. Land is mostly rented on a yearly basis and in many cases the arrangement may also allow the dairy farmer to bring any excess slurry to fertilise the land where the potatoes are grown. On average, surveyed dairy farms cooperated with 1 arable farm renting them approximately 6 hectares of land for potato production whereas surveyed arable farms cooperated with up to 32 dairy farms renting approximately 144 hectares of land for potato and silage maize production. More details of the land renting strategy are provided in supplementary table S 5.

The stocking rate on cooperating dairy farms was similar to that on non-cooperating dairy farms (Table 5). The UAA of cooperating arable farms is three times the size of the area for non-cooperating arable farms but about 85% of the cooperating arable farms' land area is rented from neighbouring dairy farmers. This has allowed cooperating arable farms to become highly specialised in potato production as they can have very long potato-based crop rotations that would not otherwise be possible. Land use diversity, as estimated using the Shannon Diversity Index, was similar on non-cooperating and cooperating dairy farms. However, land use diversity was higher on non-cooperating arable and mixed dairy farms than on cooperating arable farms due to these farms having specialised in potato production as a result of cooperation (Table 5).

Table 5. Characteristics of Winterswijk farm groups; mean values ± standard deviations

Farm characteristic	Non-cooperating, specialised dairy	Non-cooperating, specialised arable[a]	Mixed dairy	Cooperating, specialised dairy	Cooperating, specialised arable
Utilised agricultural area (ha)	67 ± 23	75 ± 0	52 ± 25	72 ± 42	218 ± 150
Stocking rate (LU ha^{-1})	2.07 ± 0.37	-	1.31 ± 1.08	2.12 ± 0.62	-
Milk production per cow (lit)	7991 ± 1061	-	7072 ± 2103	8833 ± 316	-
Permanent grassland (%)	62 ± 19	0 ± 0	58 ± 23	68 ± 10	0 ± 0
Temporary grassland (%)	11 ± 17	3 ± 0	4 ± 8	2 ± 3	0 ± 0
Silage Maize (%)	25 ± 4	0 ± 0	6 ± 6	23 ± 16	21 ± 13
Potatoes (%)	1 ± 2	38 ± 0	0 ± 0	0 ± 0	74 ± 8
Wheat, barley, sugar beet (%)	2 ± 2	42 ± 0	3 ± 4	6 ± 10	3 ± 5
Shannon diversity index	0.85 ± 0.37	1.24 ± 0	1.09 ± 0.48	0.98 ± 0.2	0.63 ± 0.14

[a] Surveyed farms in this group were from outside - but close to - the Winterswijk municipality

Potential benefits of land renting between specialised farms were assessed via hypothesis testing. We firstly hypothesised that if arable farmers rent land from dairy farmers it will result in: 1) longer crop rotations; and 2) lower cropping frequency of potatoes and hence a lower incidence of soil-borne diseases on sensitive crops such as potatoes (as indicated by lower fungicide or insecticide use on these crops). The results showed that both cooperating arable and dairy farms have longer crop rotations than their non-cooperating counterparts (Figure 2(a) and Figure 2(b)). Cooperation allows arable farms to become more specialised in potato production and expand the area on which they grow potatoes. Results also showed that the cropping frequency of potatoes was lower on both cooperating arable (0.24) and dairy (0.17) farms than on non-cooperating arable (0.29) farms. Cropping frequency of potatoes was calculated by dividing the number of years of potatoes in the crop rotation by the total duration of the rotation. Even though longer crop rotation duration and lower cropping frequency of potatoes was observed on cooperating farms, it did not result in reduced numbers of pesticide applications on potatoes. There were 13 pesticide applications per year on potatoes in both non-cooperating arable and cooperating dairy farms compared to 13.8 applications per year on cooperating arable farms (this high application frequency is a result of fungicide use against phytophthora on potatoes). It appears that any reduction in the incidence of soil-borne diseases that might occur as a result of the lengthening of crop rotations and lowering of potato cropping frequency have not been accounted for in the pest management plans of cooperating arable farms.

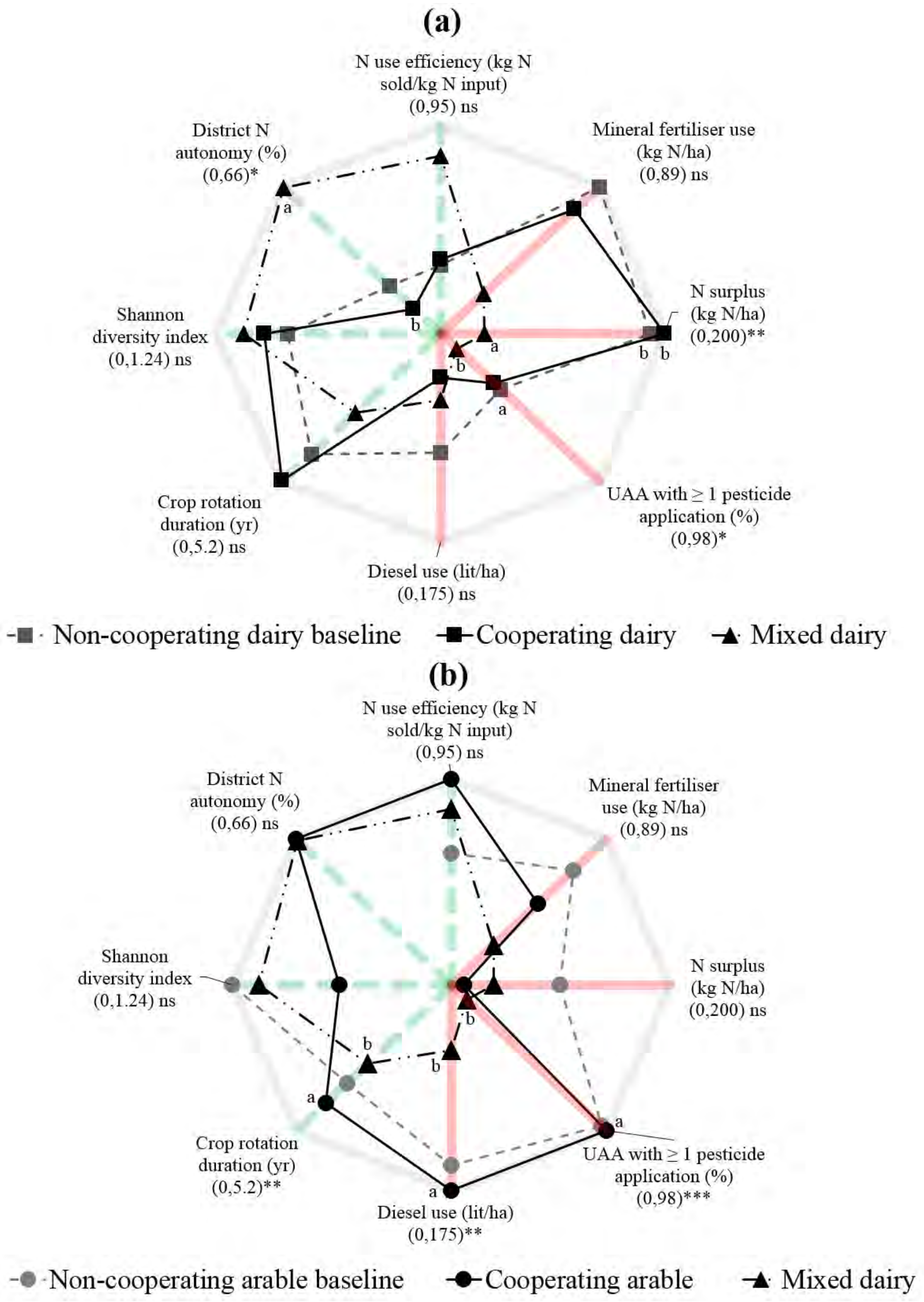

Figure 2. Comparison between Winterswijk farm groups: radar chart (a) compares non-cooperating, cooperating and mixed dairy farms; and radar chart (b) compares non-cooperating

and cooperating arable farms and mixed dairy farms. Higher indicator values on green axes are indicative of better environmental performance (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of poorer environmental performance (i.e. less self-sufficient in agricultural inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for $P<0.1$, ** for $p<0.05$, * for $p<0.01$ and ns for non-significant). The min and max value for each indicator's axis is provided in brackets after the indicator label.**

We also expected that the inclusion of crops such as potatoes in the grassland based rotations of cooperating dairy farms would: 1) improve weed control as a result of ploughing at time of potato planting; and 2) reduce fuel use on cooperating dairy farms as ploughing is undertaken by arable farmers. Results confirmed that the number of herbicide applications at the time of grassland renewal was lower on cooperating dairy farms (0.06 per year) than on non-cooperating dairy farms (0.3 per year) and that diesel use per hectare was much lower on cooperating dairy farms than it was on non-cooperating dairy farms (Figure 2(a)), although the difference was not identified as statistically significant. The magnitude of the decrease in diesel use suggests that there may be other factors at play that are partly responsible for the lower diesel use on cooperating dairy farms. One such factor is the preference for hiring contractors on cooperating dairy farms which results in more expensive contractor bills but lower on-farm consumption of diesel.

It was lastly hypothesised that the renting of dairy fields by arable farmers for potato growing would reduce mineral fertiliser use on cooperating arable farms as they can rely instead on slurry applied by dairy farmers and on legacy effects of historical applications of slurry on grasslands (e.g., high soil organic matter on ploughed grassland). Results indeed showed that mineral N fertiliser use was lower on cooperating arable farms than on specialised arable farms (Figure 2(b)).

Overall, mixed farms performed better in terms of environmental indicators and intensity indicators than all other farm groups while the differences between cooperating and non-cooperating dairy farms were small and rarely identified as statistically significant.

3.3 Animal exchanges between lowland and mountainous areas (Thurgau and Grisons, Switzerland)

The stocking rate is similar in the two lowland dairy groups and higher than in the mountain farm groups (Table 6). The two lowland dairy farm groups have roughly the same land area dedicated to cropping activities but the cooperating farms dedicate a greater land area to more profitable root crops (potatoes and sugar beet). Land use diversity, as estimated using the Shannon Diversity Index, is higher on cooperating than on non-cooperating lowland dairy farms due to the different crop species being grown on similar size areas (as opposed to some crop species being grown on a very large area).

Table 6. Characteristics of the Swiss farm groups; mean values ± standard deviations

Farm characteristic	Non-cooperating lowland dairy (baseline)	Non-cooperating mountain dairy (baseline)	Cooperating lowland dairy (no heifers)	Cooperating mountain heifer rearing
Agricultural Area (ha)	50 ± 19	38 ± 13	40 ± 14	39 ± 11
Stocking rate (LU ha^{-1})	2.63 ± 0.76	1.66 ± 0.50	2.68 ± 0.57	1.48± 0.24
Milk production (L ha^{-1})	12435 ± 2859	7337 ± 3831	14427 ± 1920	-
Permanent grassland (%)	52 ± 23	79 ± 30	42 ± 12	89 ± 17
Temporary grassland (%)	10 ± 12	13 ± 19	22 ± 7	3 ± 3
Silage Maize (%)	10 ± 10	8 ± 11	11 ± 11	4 ± 7
Wheat and barley (%)	13 ± 9	0 ± 0	11 ± 7	5 ± 8
Sugar beet and potatoes (%)	2 ± 4	0 ± 0	9 ± 8	0 ± 0
Corn maize (%)	4 ± 6	0 ± 0	0 ± 0	0 ± 0
Shannon diversity index	1.22 ± 0.36	0.43 ± 0.53	1.38 ± 0.15	0.37 ± 0.54

Potential benefits of animal exchanges between lowland and mountainous farms were assessed via hypothesis testing. In the case of cooperating lowland dairy farms, it was hypothesised that if the freed up land previously occupied by heifers is used for cash cropping then farm income will increase, or, if the land is used for feed crops; then concentrate feed autonomy will improve; and nutrient cycles may become more closed. Contrary to the hypothesis, it appears that cooperating lowland dairy farms have opted not to increase the area on which they grow crops (Table 6), but instead have opted to use the land formerly occupied by heifers to increase the number of milking cows on the farm. This is evidenced by an increase in number of milking cows per hectare of forage area in the cooperating lowland dairy group (2.37) relative to the non-cooperating lowland dairy group (1.99) (Figure 3). Therefore, instead of the expected increase in crop production area, there is an increase in milk production per hectare on cooperating lowland dairy farms (Table 6). Consequently, net income per hectare is higher on these farms (Figure 3) due to 1) increased milk production per hectare; and 2) increased production of more lucrative cash crops, such as sugar beet and potatoes (Table 6). Milk production per cow was the same in non-cooperating and cooperating lowland dairy farms.

Contrary to expectations, concentrate feed autonomy was lower in the cooperating dairy farms (Figure 3). This was due to an increase in land area under labour intensive cash crops, such as potatoes and sugar beet at the expense of feed crops, such as barley and grain maize. The absence of heifers from cooperating dairy farms appears to have afforded farmers not only the time and land to increase milk production but also the time to grow more labour intensive cash crops. Even though concentrate feed autonomy was lower on cooperating lowland dairy farms compared to non-cooperating lowland dairy farms, the amount of imported concentrates consumed per livestock unit (LU) was lower on the cooperating lowland farms (Figure 3). It would appear that cooperation has allowed lowland dairy farms to substitute expensive imported concentrates in the feed ration with home-grown forage.

Finally, results showed that cooperation resulted in more balanced nutrient management, as is evidenced by a lower N surplus per hectare on cooperating lowland dairy farms than on non-cooperating lowland dairy farms (Figure 3). The N surplus on a product output basis was also lower on cooperating lowland dairy farms (1.12 compared to 2.18 kg N /kg N in sold products). The probable reasons for the observed lower N surpluses on cooperating lowland dairy farms are differences in the operational management of N (i.e. lower amount of N imported in concentrate feeds), removal of (unproductive) heifers from the herd and increased export of N through milk and cash crop sales. This is in line with the findings of Nevens *et al* (2006), who showed that lower N surpluses on progressive specialised dairy farms (where progressive farms were defined as the 10 % of the farm group set with the lowest N surplus in relation to their production intensity) were due to considerably lower use of concentrate feed N and fertiliser N and, to a lesser extent, in a lower share of heifers in the herd. Nitrogen use efficiency was considerably higher on cooperating lowland dairy farms than on non-cooperating lowland dairy farms (Figure 3) due to cooperating lowland dairy farms having greater temporary grassland area in the crop rotation (Table 6), lower concentrate feed consumption per livestock unit (Figure 3), and greater export of N via the sale of cash crops.

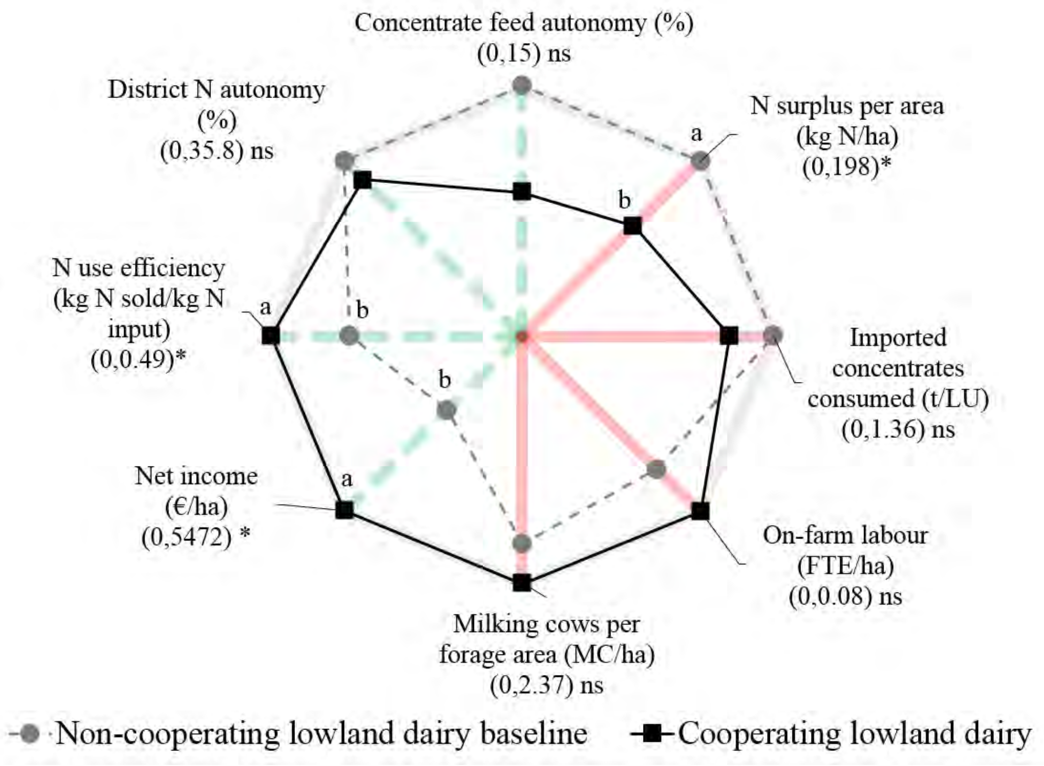

Figure 3. Comparison between non-cooperating lowland dairy farms and cooperating lowland dairy farms in Canton Thurgau, Switzerland. Higher indicator values on green axes are indicative of better environmental and economic performance (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of poorer environmental and economic performance (i.e. less self-sufficient in agricultural inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1 and ns

for non-significant). The min and max value for each indicator's axis is provided in brackets after the indicator label.

By comparing the grazing regime and the amount of cut forages consumed per LU in cooperating and non-cooperating lowland dairy farms it becomes apparent why cooperating lowland farms feed less imported concentrates per LU. Cooperating lowland dairy farms have a larger pasture area for dairy cows (18.2 ha compared to 8.2 ha), and this area does not have to be shared with heifers. As a result, milking cattle on cooperating lowland dairy farms can spend more time grazing (approximately 4.3 hrs per day compared to 3.3 hrs per day). The total plant material fed per livestock unit (including grazed pasture and home-grown and imported plant materials) is higher in the cooperating lowland dairy group than in the non-cooperating lowland dairy group, thus allowing the former to import less concentrate feed. The key point to be taken from this type of cooperation is that animal exchange allows farms to optimise the use of grasslands. This is further evidence of the potential for improved efficiency via among-farm cooperation that allows individual farms to specialise in either dairy production or heifer rearing.

For mountain farms, we hypothesised that a switch from dairying to heifer rearing will reduce workload thus allowing farmers to: 1) increase their off-farm income; 2) optimise the use of home-grown feed resources; and 3) reduce external inputs of concentrate feed. Results confirmed all these expectations (Figure 4): the mountain heifer rearing farms have lower on-farm labour per hectare which allows them to take up employment outside the farm; and lower imported concentrates consumed per LU. These findings are probably because cooperation allowed mountain farmers to access additional resources or to better exploit their natural resource base. For instance, rearing of heifers was far less time consuming than producing milk and the stocking rate of heifers was well matched to the mountain farms natural capacity to produce forages. Specialising in heifer rearing via animal exchange allows mountain farmers to reduce their intensity of production to a level that is more in line with the resources they have at their disposal. The result is a more profitable enterprise and free time to take up work outside of the farm.

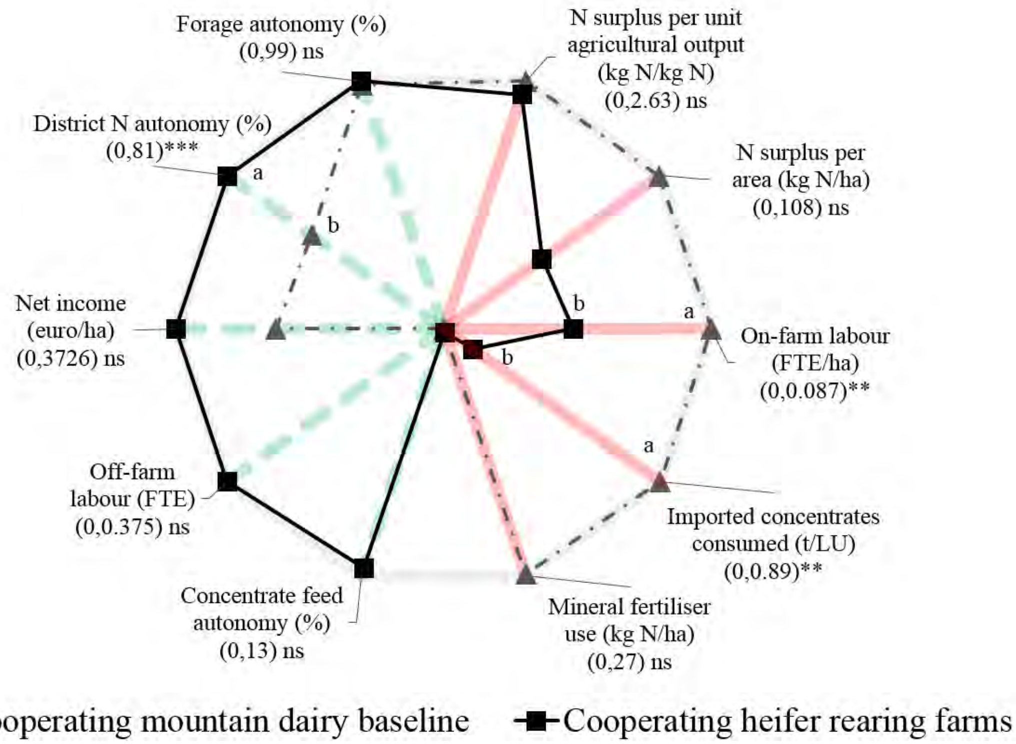

Figure 4. Comparison between non-cooperating mountain dairy farms and cooperating mountain heifer rearing farms in Canton Grisons, Switzerland. Higher indicator values on green axes are indicative of better environmental and economic performance (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of poorer environmental and economic performance (i.e. less self-sufficient in agricultural inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1, ** for p<0.05, * for p<0.01 and ns for non-significant). The min and max value for each indicator's axis is provided in brackets after the indicator label.**

3.4 Industrially mediated transfers of dehydrated fodder (Brittany, France)

Cooperation via the dehydration facility provides high quality forages for milking cows and aims to improve forage autonomy and protein feed autonomy when alfalfa is grown. Farmers sign a 5-yr contract with the cooperative in which they agree to provide land at the disposition of the cooperative for production of forage and/or miscanthus. Dehydrated forages are usually returned to the same farm on which they were grown. The planting and harvesting of the perennial crop, miscanthus, is carried out by the cooperative and generally displaces the annual crops - silage maize and wheat. The average transport distance by road between the cooperative dehydration facility and cooperating farms was approximately 15 km. The cooperating farms had approximately 10% of their UAA growing crops dehydrated by the cooperative. More descriptors of the cooperation strategy are provided in supplementary table S 6.

The stocking rate and number of milking cows per hectare was significantly higher in the cooperating farm groups than in the baseline group (Table 7). Feed concentrates fed per livestock unit were lowest in the baseline group: baseline dairy farms were generally less intensive and had a higher share of UAA under permanent grassland (Table 7). The lower milk production per hectare in the baseline group may be a result of these farms practicing less intensive livestock production, feeding lower amounts of concentrates per livestock unit (Table 7).

Table 7. Characteristics of Brittany farm groups; mean values ± standard deviations

Farm characteristic	Baseline Dairy[a]	Cooperating dairy farms growing alfalfa and miscanthus[b]
Utilised agricultural area (ha)	76 ± 19	100 ± 44
Bovine stocking rate (LU ha^{-1})	1.57 ± 0.30	1.77 ± 0.42
Milk production (lit ha^{-1})	5508 ± 1352	6625 ± 1138
Feed concentrates (kg LU^{-1} $year^{-1}$)	680 ± 216	860 ± 361
Permanent grassland (%)	47 ± 4	29 ± 10
Silage maize (%)	28 ± 5	31 ± 6
Wheat (%)	21 ± 5	24 ± 5
Alfalfa (%)	1 ± 2	7 ± 4
Miscanthus (%)	0	1.4 ± 2.1

[a] Two farms in this group also stocked pigs and one farm had a small poultry enterprise.

[b] One farm in this group also stocked pigs.

Potential benefits of industrially mediated transfers of dehydrated fodder were assessed via hypothesis testing. We firstly expected that cooperation would: 1) help to increase milk yield and forage autonomy on cooperating dairy farms relative to their non-cooperating counterparts; and 2) improve the ratio of grass/alfalfa to silage maize, thus lowering input use. Results showed that the milk yield per cow in the cooperating farm group was slightly higher than in the non-cooperating baseline farm group but the difference was not statistically significant (Figure 5). This may be related to higher intensification in cooperating farms (e.g. related to higher amount of imported concentrates, higher animal renewal rate, more frequent use of medicines, etc). In terms of forage autonomy both groups were 100 % autonomous and this precluded any improvement in forage autonomy as a result of cooperation. The second part of the hypothesis was proved false in that the cooperating farm group did not have a higher ratio of grass/alfalfa to silage maize compared to the non-cooperating baseline group (Figure 5). Therefore, cooperation did not have the effect of lowering input use: no. of pesticide applications on silage maize (4.8 compared to 3.7), mineral N fertiliser use per hectare (Figure 5) and imported concentrates consumed per livestock unit (Figure 5) were all higher in the cooperating farm group relative to the baseline group, suggesting more intensive operations in cooperating farms.

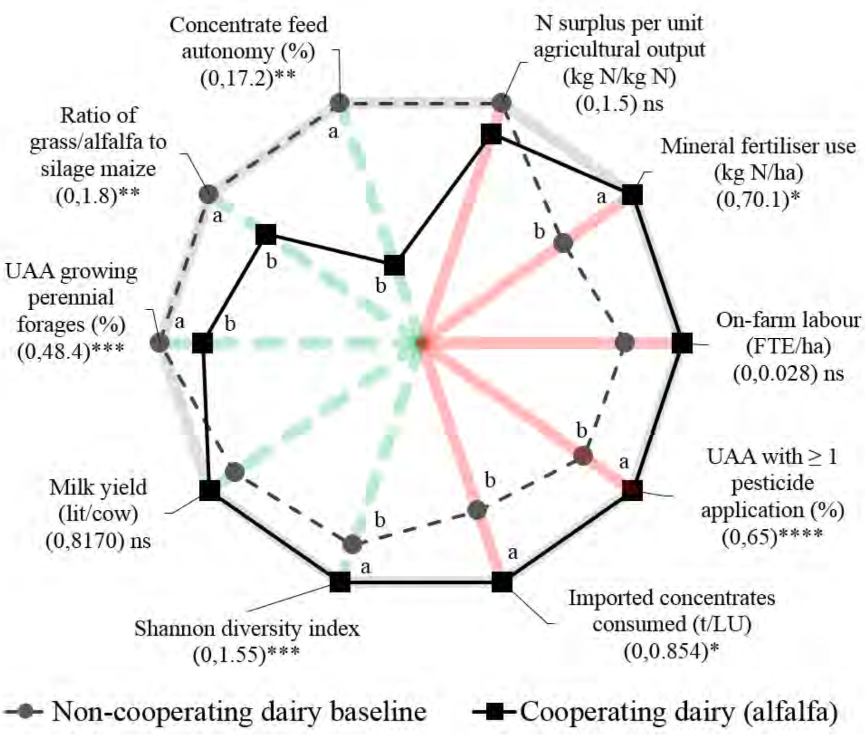

Figure 5. Comparison between the non-cooperating baseline farm group and the cooperating farm group in Brittany, France. Higher indicator values on green axes are indicative of better environmental and economic performance (i.e. more diverse, productive, autonomous and efficient) whereas higher indicator values on red axes are indicative of poorer environmental and economic performance (i.e. less self-sufficient in inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1, ** for p<0.05, * for p<0.01, **** for p<0.001 and ns for non-significant). The min and max value for each indicator's axis is provided in brackets after the indicator label.**

It was secondly hypothesised that the introduction of alfalfa in crop rotations would: 1) help to reduce the need for external feed inputs such as soybean meal imported from abroad; and 2) reduce farm workload. However, results showed that livestock on cooperating farms consumed more imported concentrates (Figure 5) and soybean (0.35 t/LU compared to 0.27 t/LU). These results illustrate the higher intensity of farming on cooperating farms relative to non-cooperating farms. Results also showed that total labour per hectare (Figure 5) and per LU (data not shown) was higher in the cooperating farm group than in the non-cooperating baseline group but the difference was not statistically significant. It would appear that the expected decreases in external input use and labour input on cooperating dairy farms were not realised because of higher numbers of milking cows per hectare in the cooperating farm group (Table 7).

It was lastly hypothesised that the increase in area growing alfalfa and miscanthus in the cooperating group would: 1) help to improve land use diversity; and 2) increase the potential for carbon sequestration. The Shannon Diversity Index was indeed higher for cooperating farms growing alfalfa (and sometimes miscanthus) than for the non-cooperating baseline farms (Figure 5). However, the potential to sequester carbon in soil (estimated using the share of UAA under perennials as a proxy) was not higher in cooperating farm group relative to the baseline group (Figure 5). The higher share of UAA under arable-arable rotation in the cooperating farm group (37 %) is further evidence of the lower potential for carbon sequestration in this group compared to the baseline group (17 %).

The overall trend is one of intensification on cooperating dairy farms: it would appear that the facility to have forage crops dehydrated by Coopédom incentivises farmers to replace lower intensity permanent grassland area with forage crops that are more input intensive. This increases the livestock carrying capacity of their land allowing them to increase their stocking rate (Table 7). As a result these farms import more concentrate feed per LU and have a reduced area under permanent grassland relative to baseline farms

4. Discussion

4.1 Summary of the main findings and consequences for dairy and arable farming systems

Cooperation between specialised farms via the four crop-livestock integration strategies assessed, generally allowed farmers to access additional local resources, such as land, labour, organic nutrients or livestock feed. The farmers' decisions about how to manage or deploy these extra resources largely determined the consequences for the farms: basically, farmers could opt to either diversify their farming system - therefore tending toward greater farm autonomy - or intensify their farming system via increased specialisation. Table 8 summarises the resources made available through each crop-livestock integration strategy as well as how the farmers deployed those resources. In three of the four crop-livestock integration strategies assessed (namely: material exchange, animal exchange and industrially mediated transfer of dehydrated forages) there was a marked increase in farming intensity on cooperating farms relative to non-cooperating farms, as indicated by farmers opting to use newly accessed resources to increase: 1) the number of milking cows per hectare on dairy farms; and 2) the cropping intensity on arable farms. Two of the integration strategies (namely: animal exchange and land renting) facilitated increased specialisation in milk production, heifer rearing or potato production. As a result of farmers opting to use the local resources, made available via cooperation, to intensify and specialise as opposed to diversifying their operations, some of the expected benefits of recoupling crop and livestock production via farm cooperation were not realised, such as, lower external input use and improved N fertiliser autonomy. Indeed, specialisation usually leads to lower costs per unit product (due to economies of scale) but could potentially increase the vulnerability of individual farms and their capacity to handle sudden price fluctuations, which are expected to become more frequent in the future. Specialisation also creates technical efficiencies that can reduce labour input thereby freeing up labour resources to be utilised elsewhere on or off the farm – increasing net income.

Crop-livestock integration strategy	Local resources accessed		Deployment of resources by farmer	Main consequences for the farming system	
	Dairy Farm	**Arable Farm**		**Benefits**	**Drawbacks**
Material exchange	Land (outlet for manure)		Export excess manure to land located off-farm	Increased milk production; reduced pesticide applications	Increased stocking rate; increased mineral N fertiliser use per ha
		Manure	Incorporated in soil to supply crop nutrients	Increased SOM level	Increased tillage and irrigation; increased mineral N fertiliser use per ha
	Straw input		Animal bedding		
		Outlet for straw			
Land renting		Land	Increased potato production	Access to fertile land for potato production; longer crop rotations with lower frequency of potatoes;	Increased farm exposure to potato production problems.
		Slurry and legacy nutrients	Increase supply of nutrients to potato crop	Lower mineral fertiliser use	
	Labour and machinery		Ploughing of grasslands	Lower fuel use for dairy farmer; lower herbicide use (grassland)	
Animal exchange	Land (lowland)		Increase in milking herd size	Increased milk production; increased net income per ha; lower N surplus per ha	Increased specialisation in dairy production
	Labour and time management (lowland)		Increase milking herd size and production of intensive cash crops	Optimised use of grasslands; increased N use efficiency	
	Land (heifer farm)		Stocking of heifers on previously inaccessible steep slopes	Optimised use of grasslands; lower imported concentrates consumed per LU	
	Time management (heifer farm)		Take up work outside the farm	Increased off-farm income; lower on-farm labour per hectare	

Industrially mediated transfers of dehydrated fodder	High quality dehydrated alfalfa and other crops	Increase in milking herd size	Increased land use diversity	Increased input use per ha (concentrate feed, pesticides, fertiliser and labour); lower % UAA growing perennial forages;

Table 8. Local resources accessed through among-farm cooperation, their deployment by the farmer and subsequent consequences for the farming system.

This study provides first empirical evidence that recoupling crop and livestock production via cooperation among specialised farms doesn't lead to many environmental benefits but instead helps specialised dairy and arable farmers to further intensify and specialise their farming systems through more intensive use of available local resources. With the exception of the food provisioning service, cooperation didn’t result in improved ecosystem services provision. Cooperation did however help improve resource use efficiency by enabling farmers to access previously untapped on-farm resources (such as, Alpine grassland) and better utilise nutrients in by-products of production such as manure. Intensification and specialisation that is facilitated by optimised use of home-grown feed resources and available land and labour resources can be considered more sustainable than intensification that relies primarily on increasing inputs from outside. Indeed, benefits of cooperation were generally observed on those farms that used cooperation to replace some external inputs to production with some locally sourced inputs.

Beyond the general conclusion that cooperation among specialised farms doesn't lead to many environmental benefits, we found that the level of benefits were specific to the crop-livestock integration strategy employed: for animal exchange, the benefits of cooperation included increased productivity, increased N use efficiency and lower N surplus per land area farmed; while for industrially mediated transfer of dehydrated forages, the benefits were restricted to increased land use diversity (Table 8). Cooperation via animal exchange allowed farms to increase production without an increase in N surplus per hectare relative to non-cooperating farms (Table 8). In contrast, no benefits of cooperation through material exchange were identified on cooperating arable farms. Except for reduced use of pesticides, there were no obvious environmental benefits of material exchange observed on dairy farms. This was due to cooperation being strongly orientated towards increasing the outputs of manure from an enlarged dairy system without attempting to increase the local feed input. Implementing the material exchange strategy with the aim of meeting the manure management needs of the dairy farm while neglecting the potential for cooperating arable farms to provide forages resulted in a number of drawbacks for the farming system (Table 8). Material exchange could be improved if manure were to be exchanged for alfalfa instead of straw, as this would help ensure easy access to sufficient livestock feed, while also having more balanced N exchanges between cooperating farms.

Even though cooperation was accompanied by intensification and specialisation that limited farm diversification, it did lead to some environmental benefits by improving resource use efficiency per unit of agricultural product produced. Cooperation ensured that a greater part of the inputs required for intensification were locally sourced. This may be why cooperation sometimes led to metabolic benefits for the farming systems concerned. Although it is unclear if cooperation helped farmers to intensify their system, or if cooperation is required to sustain already intensive systems, and if cooperating farms were more prone to adopt innovative practices, these results provide a platform to discuss integration strategies between crop and livestock and to design resource efficient farming systems at different spatial scales.

4.2 Possible implications for the period after the milk quota abolition in Europe

Simulation results from a number of studies (Chantreuil et al., 2008; Kempen et al., 2011; Réquillart et al., 2008; Witzke and Tonini, 2009) indicate that the abolition of the milk quota regime will have the effect of increasing milk production in the EU by between 3 and 5 % and reducing raw milk prices by between 7 and 10 % on average. This fall in milk prices in the wake of the abolition of the milk quota regime will put pressure on farmers to either increase milk production (while reducing unit cost, in an economy of scale perspective, in competitive regions) or to diversify their systems by growing cash crops (in an economy of scope perspective, in less competitive regions). In this context, cooperation with arable farmers can provide dairy farmers with the resources and sometimes infrastructure they require to either intensify operations (e.g. increase milk production) or diversify income streams (e.g. introduce cash crops). So, by cooperating with neighbouring arable farmers, specialised dairy farmers should have greater flexibility to adjust their system in response to changing prices and regulations without greatly increasing direct production costs. The forms of cooperation assessed in this study revealed that cooperating farms tend to be more intensive and less diversified than non-cooperating farms but further studies are required to see if this finding applies to other forms of cooperation between farms and if it applies evenly in competitive and less competitive regions.

In the absence of the milk quota regime, land will likely be the most scarce production factor as farmers seek to increase their milk output. Dairy farmers need enough land for feeding the animals with forages but also to comply with the EU nitrate regulatory limits, expressed per hectare of land (Boere et al., 2015). It follows then that with the abolition of milk quotas, nitrate regulations, may become the limiting factor for milk production (Boere et al., 2015). Therefore, options that help farmers to increase their production while limiting their N surplus per hectare will likely be adopted by farmers (Gaigné et al., 2011). As such, the crop-livestock integration strategy of animal exchange shows potential as a way of sustainably intensifying production as it allowed farms to increase their product output per hectare (Table 6) without increasing their N surplus per hectare (Figure 3 and Figure 4). The N surplus per hectare was lower on cooperating farms than on non-cooperating baseline farms thus showing that cooperation via animal exchange can help to protect water quality.

5. Conclusions

This research has shown that cooperation between specialised crop and dairy livestock farms gives them access to local resources, such as manure and livestock feed, which could potentially replace some purchased inputs of chemical fertiliser and concentrate feeds. However, farm surveys showed that resources accessed via cooperation were generally employed to intensify, and in some cases specialise, operations as opposed to diversifying them. Therefore, some of the expected environmental benefits of cooperation were not realised, such as, lower external input use and improved fertiliser autonomy.

These results provide key elements from farming system analysis to anticipate the potential consequences of milk quota abolition in Europe. They show that farmers' decisions about how to face the widened competitive gap between producing regions and how to utilise the resources freed up by the milk market liberalisation will be key in future environmental performances of European agriculture. This study provides timely knowledge about the benefits associated with between farm collaboration to promote integration between crops and livestock and about the difficulties that farmers encounter when cooperating with other farmers to integrate their productions. As such, these results are likely to play a critical role in farming system design operations and public policy elaboration to overcome these difficulties.

6. References

Barrantes, O., Ferrer, C., Reiné, R., Broca, A., 2009. Categorization of grazing systems to aid the development of land use policy in Aragon, Spain. Grass Forage Sci. 64, 26–41. doi:10.1111/j.1365-2494.2008.00666.x

Bell, L.W., Moore, A.D., 2012. Integrated crop–livestock systems in Australian agriculture: Trends, drivers and implications. Agric. Syst. 111, 1–12. doi:10.1016/j.agsy.2012.04.003

Bell, L.W., Moore, A.D., Kirkegaard, J.A., 2014. Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. Eur. J. Agron. 57, 10–20. doi:10.1016/j.eja.2013.04.007

Benin, S., Smale, M., Pender, J., Gebremedhin, B., Ehui, S., 2004. The economic determinants of cereal crop diversity on farms in the Ethiopian highlands, in: Agricultural Economics. pp. 197–208. doi:10.1016/j.agecon.2004.09.007

Boere, E., Peerlings, J., Reinhard, S., Heijman, W., 2015. The dynamics of dairy land use change with respect to the milk quota regime. Eur. Rev. Agric. Econ. 1–24. doi:10.1093/erae/jbv002

Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., Tichit, M., 2014. Agroecological principles for the redesign of integrated crop–livestock systems. Eur. J. Agron. 57, 43–51. doi:10.1016/j.eja.2013.09.010

Chantreuil, F., Donnellan, T., Leeuwen, M. Van, Salamon, P., Tabeau, A., Bartova, L., 2008. EU Dairy Quota Reform – AGMEMOD Scenario Analysis 1–15. online: http://purl.umn.edu/43655

De Moraes, A., Carvalho, P.C. de F., Anghinoni, I., Lustosa, S.B.C., Costa, S.E.V.G. de A., Kunrath, T.R., 2014. Integrated crop–livestock systems in the Brazilian subtropics. Eur. J. Agron. 57, 4–9. doi:10.1016/j.eja.2013.10.004

Eurostat, 2013. Agriculture, forestry and fishery statistics pocketbook. European Union. doi:10.2785/45595

FAO, 1997. Irrigation in the near east region in figures. Water Report no. 7. Rome. http://www.fao.org/docrep/w4356e/w4356e00.HTM

Federal Statistics Office, 2013. Farm Structure Survey.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–42. doi:10.1038/nature10452

Franzluebbers, A.J., Lemaire, G., de Faccio Carvalho, P.C., Sulc, R.M., Dedieu, B., 2014. Toward agricultural sustainability through integrated crop–livestock systems. II. Production responses. Eur. J. Agron. 57, 1–3. doi:10.1016/j.eja.2014.05.004

Gaigné, C., Le Gallo, J., Larue, S., Schmitt, B., 2011. Does regulation of manure land application work against agglomeration economies? Theory and evidence from the French hog sector. Am. J. Agric. Econ. 94, 116–132.

Havet, A., Coquil, X., Fiorelli, J.L., Gibon, A., Martel, G., Roche, B., Ryschawy, J., Schaller, N., Dedieu, B., 2014. Review of livestock farmer adaptations to increase forages in crop rotations in western France. Agric. Ecosyst. Environ. 190, 120–127. doi:10.1016/j.agee.2014.01.009

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems. Sci. 327 , 822–825. doi:10.1126/science.1183725

Kempen, M., Witzke, P., Pérez Domínguez, I., Jansson, T., Sckokai, P., 2011. Economic and environmental impacts of milk quota reform in Europe. J. Policy Model. 33, 29–52. doi:10.1016/j.jpolmod.2010.10.007

Korevaar, H., Geerts, R.H.E.M., 2012. Experiences with ecosystem services on farms: a pilot study towards CAP reform., in: In: Grassland - a European Resource? Proceedings of the 24th General Meeting of the European Grassland Federation, Lublin, Poland, 3-7 June. - Grassland Science in Europe 17. Zürich□: European Grassland Federation,. pp. 756–758.

Lebacq, T., Baret, P. V, Stilmant, D., 2015. Role of input self-sufficiency in the economic and environmental sustainability of specialised dairy farms. Animal 9, 544–552.

Lemaire, G., Franzluebbers, A., Carvalho, P.C. de F., Dedieu, B., 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ. 190, 4–8. doi:10.1016/j.agee.2013.08.009

Maréchal, K., Aubaret-Joachain, H., Ledant, J., 2008. The influence of economics on agricultural systems: an evolutionary and ecological perspective. Work. Pap. CEB 32, 0–25.

Moraine, M., Duru, M., Nicholas, P., Leterme, P., Therond, O., 2014. Farming system design for innovative crop-livestock integration in Europe. Animal 8, 1204–1217.

Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Alder, J., Mooney, H., 2005. Agriculture. Losing the links between livestock and land. Science 310, 1621–2. doi:10.1126/science.1117856

Nevens, F., Verbruggen, I., Reheul, D., Hofman, G., 2006. Farm gate nitrogen surpluses and nitrogen use efficiency of specialized dairy farms in Flanders: Evolution and future goals. Agric. Syst. 88, 142–155. doi:10.1016/j.agsy.2005.03.005

O'Sullivan, L., Creamer, R.E., Fealy, R., Lanigan, G., Simo, I., Fenton, O., Carfrae, J., Schulte, R.P.O., 2015. Functional Land Management for managing soil functions: A case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland. Land use policy 47, 42–54. doi:10.1016/j.landusepol.2015.03.007

Oomen, G.J.M., Lantinga, E.A., Goewie, E.A., Van der Hoek, K.W., 1998. Mixed farming systems as a way towards a more efficient use of nitrogen in European Union agriculture. Environ. Pollut. 102, 697–704. doi:10.1016/S0269-7491(98)80101-2

Peyraud, J.-L., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: A review. Eur. J. Agron. 57, 31–42. doi:10.1016/j.eja.2014.02.005

Réquillart, V., Bouamra-Mechemache, Z., Jongeneel, R., Penel, C., 2008. " Economic analysis of the effects of the expiry of the EU milk quota system ." Rep. Prep. Eur. Comm. 0–98.

Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering Integrated Crop–Livestock Systems in North America. Agron. J. 99, 325–334. doi:10.2134/agronj2006.0139

Ryschawy, J., Choisis, N., Choisis, J.P., Gibon, A., 2013. Paths to last in mixed crop-livestock farming: lessons from an assessment of farm trajectories of change. Animal 7, 673–81. doi:10.1017/S1751731112002091

Ryschawy, J., Joannon, A., Gibon, A., 2014. L'exploitation de polyculture-élevage : définitions et questions de recherche. Une revue. Cah. Agric. 23, 346–356. doi:10.1684/agr.2014.0727

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M., 2014. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agric. Ecosyst. Environ. 190, 70–79. doi:10.1016/j.agee.2013.09.023

Sanderson, M.A., Archer, D., Hendrickson, J., Kronberg, S., Liebig, M., Nichols, K., Schmer, M., Tanaka, D., Aguilar, J., 2013. Diversification and ecosystem services for conservation agriculture: Outcomes from pastures and integrated crop–livestock systems. Renew. Agric. Food Syst. 28, 129–144. doi:10.1017/S1742170512000312

Schiere, J.B., Ibrahim, M.N.M., Van Keulen, H., 2002. The role of livestock for sustainability in mixed farming: Criteria and scenario studies under varying resource allocation. Agric. Ecosyst. Environ. 90, 139–153. doi:10.1016/S0167-8809(01)00176-1

Soussana, J.-F., Lemaire, G., 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. Agric. Ecosyst. Environ. 190, 9–17. doi:10.1016/j.agee.2013.10.012

Sulc, R.M., Franzluebbers, A.J., 2014. Exploring integrated crop–livestock systems in different ecoregions of the United States. Eur. J. Agron. 57, 21–30. doi:10.1016/j.eja.2013.10.007

Sulc, R.M., Tracy, B.F., 2007. Integrated Crop–Livestock Systems in the U.S. Corn Belt. Agron. J. 99, 335–345. doi:10.2134/agronj2006.0086

Tanaka, D.L., Karn, J.F., Scholljegerdes, E.J., 2008. Integrated crop/livestock systems research: Practical research considerations. Renew. Agric. Food Syst. 23, 80–86. doi:10.1017/S1742170507002165

Veysset, P., Lherm, M., Bébin, D., Roulenc, M., 2014. Mixed crop–livestock farming systems: a sustainable way to produce beef? Commercial farms results, questions and perspectives. animal 8, 1218–1228.

Villano, R., Fleming, E., Fleming, P., 2010. Evidence of farm-level synergies in mixed-farming systems in the Australian Wheat-Sheep Zone. Agric. Syst. 103, 146–152. doi:10.1016/j.agsy.2009.11.005

Witzke, H.P., Tonini, A., 2009. Milk quota expiry impacts and sensitivity analyses using the CAPSIM model. Agrarwirtschaft 58, 228–237.

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8. Supplementary Materials

<u>Additional information about case studies and crop livestock integration strategies:</u>

Ebro Basin: local cooperation through material exchange

The terms of exchange require only that the quantities of, and transport of, exchanged materials are agreed and as such no money changes hands. Even though no contractual agreements are in place the cooperation is quite stable over time. This is evidenced by farms cooperating for 11.2 years on average, with only one incidence of breakdown in cooperation during that period. Cooperation is facilitated by a short average road distance of only 5 km between cooperating farms. The carrying of the economic burden associated with transport of straw/manure and spreading of manure varied from partnership to partnership. Sometimes it was taken on wholly by one or other party and sometimes it was split between the two. The material exchange ratio of manure for straw (by weight) is approximately 5 to 1.

On average, the surveyed dairy farms cooperated with 2.7 arable farms while arable farms only cooperated with 1 dairy farm. Farm surveys showed that both farm types are heavily invested in the partnership such that cooperating dairy farms export (for exchange) approximately 61% of their total manure production, while cooperating arable farms export (for exchange) approximately 81% of their total straw production.

Winterswijk: land renting in dairy and arable farms

A minimum break period of 3 years is normally required between potato crops for disease prevention which means that small farms cannot produce enough potatoes on their own land to offset the high costs associated with potato production. By renting land from neighbouring dairy farms, arable farmers can include their potato crop in the longer crop rotation of the dairy farm while either leaving their own fields to rest or growing an alternative crop to potatoes. The dairy farmers benefit from reduced ploughing costs and an outlet for excess slurry, which they use to fertilise the potato crop. The arable farmer benefits from extended crop rotations and mineralised Nitrogen that is released in the soil at the time of ploughing up grasslands for reseeding. The arable farmer rents the land from the dairy farmer at a cost of approximately 750 €/ha. After the potatoes are harvested in August/September the field is returned to the dairy farmer at which time it is reseeded with grass by the dairy farmer.

Switzerland: animal exchanges between lowland and mountain farms

On average, lowland dairy farmers cooperate with 3 mountain rearing farms whereas mountain rearing farms cooperate with 10 lowland dairy farms. The average transport distance by road between lowland and mountain farms was approximately 125 km. Cooperating lowland farms sent 17 calves and bought back 14 pregnant heifers on average.

Domagné: industrially mediated transfers of dehydrated fodder

The Coopédom cooperative society was created to dehydrate forages. This facility allowed dairy farmers to introduce the legume crop, alfalfa, in crop rotations. Growing alfalfa is not viable in this area of France without a facility to quickly dry the harvested crop. In summary, the legume crop alfalfa cannot be grown for feeding to dairy livestock without the Coopédom cooperative society, which is owned and run by its farmer members. This is a form of industrial integration beyond the farm scale..

<u>Figures:</u>

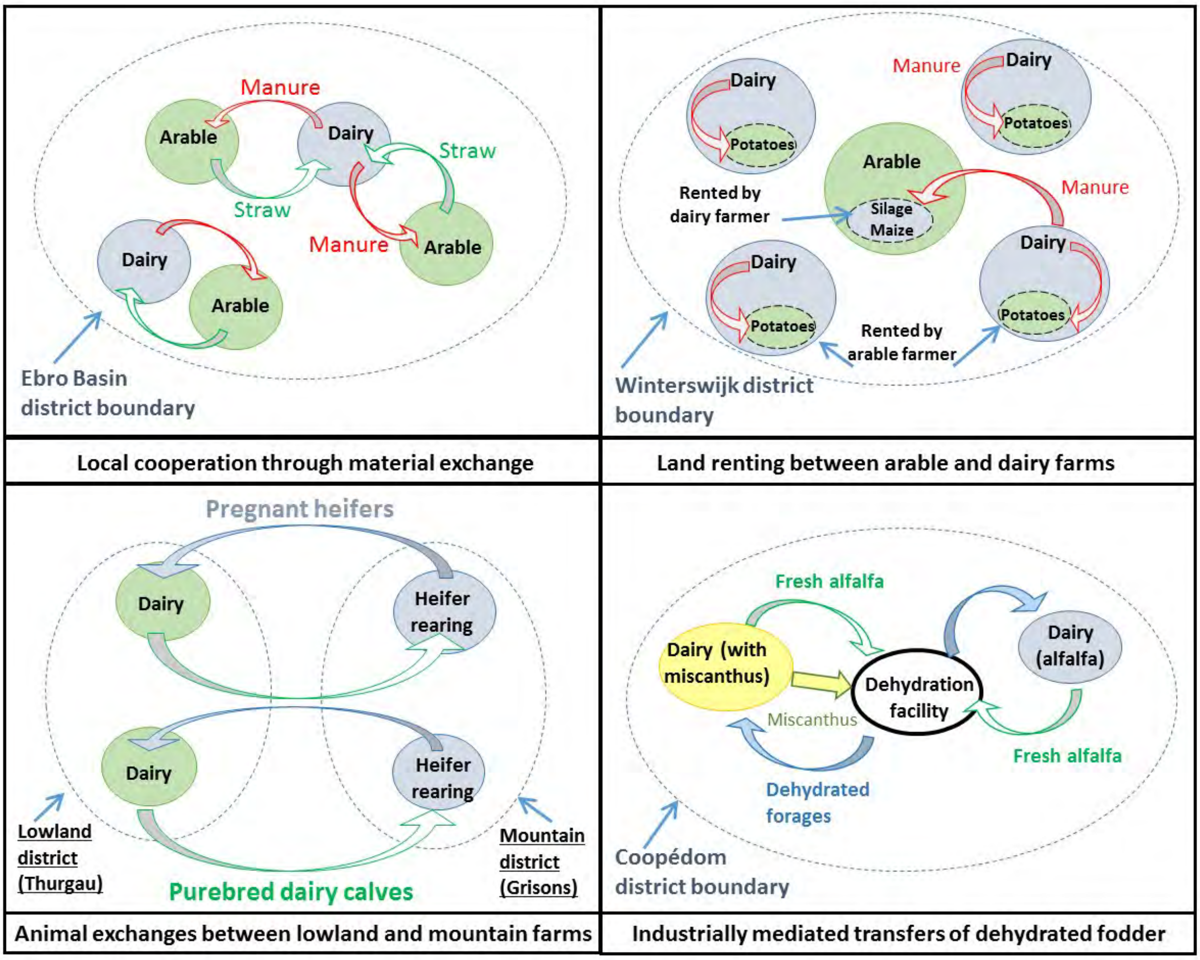

Figure S 1. Crop-livestock integration strategies under study

Tables:

Table S1. Summary of the baseline and cooperating farm groups studied in the Ebro Basin case study.

Situation	**Farm type**	**No. of farms assessed**
Baseline 1: Non-cooperating dairy	Dairy farms with only a small area dedicated to crop production, use their manure on their own land and buy in straw, grains and some fodder.	4 farms
Baseline 2: Non-cooperating arable	Arable farms with no organic fertiliser input	5 farms
Baseline 3: Within-farm mixing	Farms with both dairy animals and cereal crops, on which a significant amount of the feed and/or straw for livestock is home produced and with a significant fraction of income comes from grain sales.	4 farms
Mixing Strategy: Exchange of solid manure for straw	Specialised dairy farms that exchange solid manure for straw with specialised arable farms	5 dairy and 4 arable

Table S2. Summary of the baseline and cooperating farm groups studied in the Winterwijk case study.

Situation	Farm type	No. of farms assessed
Baseline 1: Non-cooperating dairy	Specialised dairy farms with grass/maize rotations, using the majority of their manure on their own land, buying in concentrates and not exchanging fields	4 farms
Baseline 2: Mixed dairy farms	Mixed farms (i.e. dairy farms growing cereals on their own land)	3 farms
Baseline 3: Non-cooperating arable	Specialised arable farms from outside the zone of influence that do not rent land	15 arable farms on sandy soils in eastern part of

		the Netherlands were used
Mixing strategy: Land sharing between dairy farms and arable farms	Specialised dairy farms that rent some fields to arable farms specialised in potato production	3 dairy farms and 3 arable farms

Table S3. Summary of the baseline and cooperating farm groups studied in the Swiss case study.

Situation	Farm type	No. of farms assessed
Baseline 1: Non-cooperating lowland dairy	Lowland dairy farms that raise their own heifers	4 farms
Baseline 2: Non-cooperating mountain dairy	Mountain dairy farms that raise only their own heifers.	4 farms
Mixing strategy: sale, by lowland farmers, of heifers to mountain farmers specialised in heifer rearing	Lowland dairy farmers that sell their weaned female pure bred dairy calves to mountain farmers specialised in heifer rearing, who later sell them back when pregnant and close to calving.	4 lowland dairy farms and 4 heifer rearing mountain farms

Table S4. Summary of the baseline and cooperating farm groups studied in the Coopédom case study.

Situation	Farm type	No. of farms assessed
Baseline: Non-cooperating dairy farms	Dairy farms located outside the area where Coopédom operates	7 farms
Mixing strategy: dehydration of forages and production of miscanthus for use as a biomass fuel	Dairy farms growing alfalfa for dehydration, with some farms also having silage maize and ryegrass dehydrated, and growing miscanthus	11 farms (of which, all 11 dehydrate alfalfa, 5 grow miscanthus, 6 dehydrate ryegrass and 2

		dehydrate silage maize)

Table S5. Descriptors of cooperation for Winterswijk farm groups; mean values ± standard deviations[a]

Parameter	Specialised Dairy	Specialised Arable	Mixed Dairy	Cooperating Dairy	Cooperating Arable
No. of farms cooperated with	0 ± 0	0 ± 0	0 ± 0	1 ± 0	32 ± 22
Utilised agricultural area (ha)	67 ± 23	75 ± 0	52 ± 25	72 ± 42	218 ± 150
Land rented out from yr to yr (ha)	-	-	-	6 ± 3	-
Land rented from yr to yr (ha)	-	-	-	6 ± 8	144 ± 116
Land ownership (ha)	67 ± 23	75 ± 0	52 ± 25	73 ± 36	74 ± 50

[a] The mean UAAs shown includes only the land that was farmed during the survey year (i.e. the land a farmer rented out was excluded and the land a farmer rented from another was included).

Table S6. Descriptors of cooperation for Coopédom farm groups; mean values ± standard deviations

Parameter	Farms outside Coopédom	Farms cooperating with Coopédom
Average road distance between farms and Coopédom (km)	37.5 ± 12.5	14.6 ± 7
Forage area dehydrated (% of UAA)	0	10 ± 6
Forages dehydrated (tons)	0	92 ± 55
Agricultural area harvested by Coopédom (% of UAA)	0	12 ± 7